MARS PATHFINDER MISSION OPERATIONS CONCEPT

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ABSTRACT

Mars Pathfinder is one of the first of NASA's Discovery series of low cost planetary missions. A number of innovative design, fabrication, and management techniques have been adopted during the development phase to stay within the $150M (FY'92) cost cap. With the upcoming December 1996 launch, the same faster, better, cheaper spirit is being applied to develop a low cost approach for mission operations. The operability of the Flight System and Ground Data System enable an operations architecture in which all primary activities are performed by a core group of functional generalists. This group consists of experienced development and test personnel whose skills are augmented with cross-training and contingency testing. The small size of this team combined with a flat management structure permit highly streamlined and efficient operations processes. This efficiency is critical during the surface mission when daily updates to the operational plan will occur.

INTRODUCTION

The Mars Pathfinder mission, which will place a lander on the surface of Mars in mid-1997, is an example of NASA's new commitment to low cost, exciting planetary missions. The project, currently under development at the Jet Propulsion Laboratory, is nearing launch and the start of mission operations. As a result, project personnel are developing detailed operations plans. The purpose of this paper is to describe some of these plans and the key characteristics of the Pathfinder mission operations system architecture.

MISSION OVERVIEW

One of the key drivers in developing the Mars Pathfinder mission operations architecture is the unique nature of the mission itself. The mission starts with launch from Cape Canaveral Air Station during the period from December 2-30, 1996. The launch vehicle is a three stage Delta II 7925 built by McDonnell Douglas. The spacecraft is relatively quiescent during the seven months cruise to Mars. Attitude control during cruise is performed through passive stabilization, and the spacecraft remains Earth pointed for most of cruise. No science activities are planned and the only key events are four trajectory correction maneuvers.

The spacecraft arrives at Mars on July 4, 1997, immediately enters the Martian atmosphere and lands. Entry, descent, and landing activities are controlled by on-board software, but key navigation and DSN tracking activities are performed by the operations team. The navigation requirements for Pathfinder are tighter than any previous planetary missions, but judicious use of advanced data filtering techniques has allowed the project to use relatively simple data types and minimal tracking.

The most operationally intensive part of the mission starts once the lander has successfully reached the surface. The lander's primary surface operations mission lasts for 30 sol (a sol is a Martian day - 24.7 Earth hours). The key activities performed immediately after landing include return of recorded entry science and engineering data, initiation of a high rate telecommunications link, acquisition and return of a panoramic image of the surrounding terrain, and rover deployment. Rover operations are planned for a minimum of 7 sols, with a command cycle scheduled for each day. This fast command turnaround time is a key driver on the surface operations uplink and downlink processes. Significant changes in the daily operations plan are likely because of pre-arrival uncertainty in the surface environment. An extended mission of up to one year is possible., with the focus on continued use Of the science instruments and rover.

FLIGHT SYSTEM OVERVIEW

The capabil ities of the Mars Pathfinder spacecraft, instruments, and rover are key reasons why low cost operations are possible. The flight system performs three distinct missions: cruise, Mars atmospheric entry and landing, and surface operations. Figure 1 shows an exploded view of the spacecraft. The cruise stage performs most of the cruise. functions, including attitude determination and control, midcourse guidance, telecommunications and power generation using solar arrays. The entry vehicle (including an aeroshell, backshell parachute, retrorockets, and air bags) is used to safely place the lander and rover on the surface of Mars. The lander contains the central electronics module (used to control all three phases of the mission), the radio, a rechargeable battery, solar arrays, the science instruments, and the rover. Figure 2 shows a schematic of the lander in the deployed configurat ion.

Concurrent engineering of the flight elements, GDS and Mission Operations System has resulted in a highly operable design. The spacecraft is built around a single powerful compu ter which controls the spacecraft and science instruments. The capabilities of this Loral R6000 computer allow many previously onerous ground activities to be performed on-board the space.crafl. Specific examples are on-board memory management (performed by the commercial VxWorks operating system) and high level commanding (whit]] replaces the need for expandable blocks). Flight software is also able to autonomously manage several key spacecraft functions, including fault protection, closed loop thermal control, high gain antenna pointing, attitude determination and cont rol, and control of all activities related to entry, descent, and landing. Other operability features include a simple attitude control architecture (passive spin stabilization), significant power margins (particularly during cruise), a high capacity rechargeable battery and high telemetry rate capabilities.

The rover and science instruments have also been designed with operations in mind. The rover is a semi-autonomous vehicle that does not required ground- in-the-]oop control. Rover traverses are planned using high level waypoint command s which the rover interprets and performs in a closed loop manner. Rover - lander communications are completely autonomous, with the rover serving as the link controller. The Imager for Mars Pathfinder (IMP) has been designed with closed loop temperature control for the CCD, and can be pointed in a wide range of different coordinate systems. The other science instruments are relatively a relatively simple meteorological package which does not require active control and an Alpha-Proton-Xray Spectrometer located on the rover.

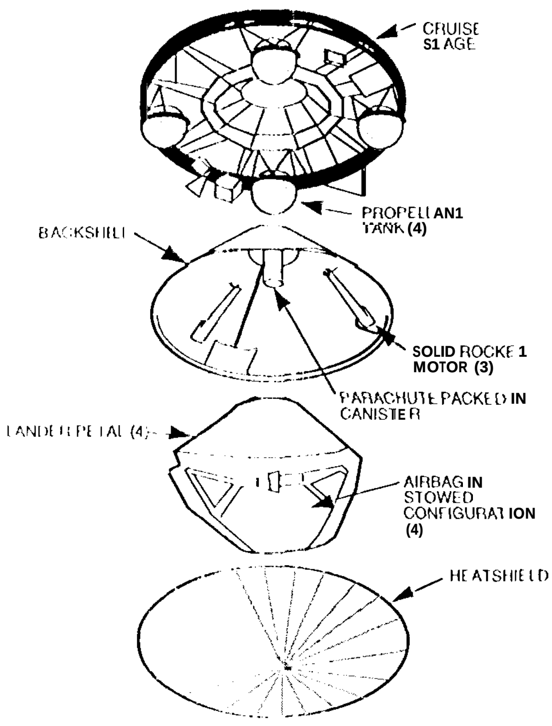

Figure I. Mars Pathfinder Flight System

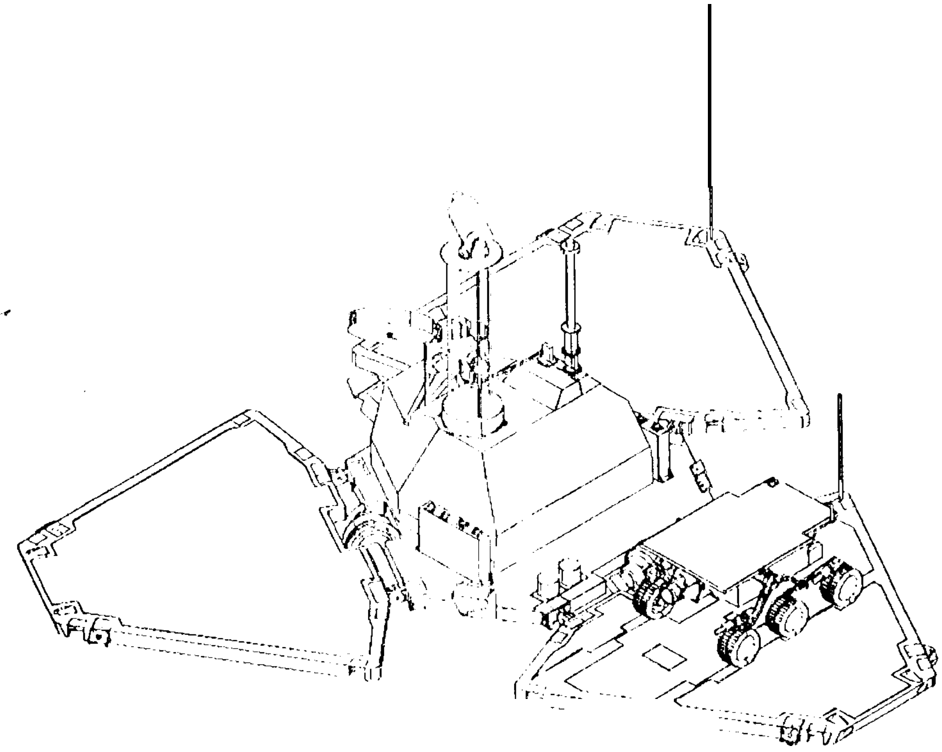

Figure 2 Lander Configuration

GROUND DATA SYSTEM OVERVIEW

The Pathfinder Ground Data System is derived from the JPL institutional Multimission Ground Data System. This inheritance was made possible by constraining the flight system to follow simple telemetry and command format guidelines (such as the use of CCSDS standards). This approach reduces the costs associated with GDS development and enables GDS personnel to focus on building additional operability features into the software. Considerable effort has been made to simplify the user interfaces and integrate the system into a unified control system. As a result, hands-on use of the GDS toolset is now possible without the need for a large staff of toolsmiths.

The uplink elements of the GDS have been integrated under a single Graphical User Interface driven control shell. This shell provides the ability to perform end-to-end planning, sequence, and command capabilities. Program to program interface issues have been virtually eliminated, and operators are free from file management concerns. A sophisticated planning tool has been developed for surface operations and will perform most of the resource management functions. High fidelity spacecraft behavior models have been incorporated into the code to reduce the need for subsystem interaction. In addition, a very capable image planning tool has been developed around a software model of the IMP. This tool can plan panoramas, generate camera commands and graphically show the resulting images. The same process was performed by hand during the Viking mission by a large group of image analysts. All uplink programs are table driven to allow for easy maintenance.

The downlink elements of the GDS have also been upgraded to provide sophisticated telemetry handling capabilities. Besides the standard telemetry processing and display capabilities, the project has developed a special tool to track the state of the spacecraft and provide quick assessments of the system level performance of the vehicle. An automated system has been developed for tracking data packets and requesting retransmission from the spacecraft. Science image processing is performed by the institutional Multimission Image Processing Laboratory using existing capabilities.

MISSION O1)'CRA"I'IONS SYSTIM ARCHITECTURE

The mission operations system architecture for Mars Pathfinder is a rather distinct departure from recent JPL experience. This is in part due to the unique nature of the Pathfinder mission, but is also driven by some key project characteristics. These include:

- The desire and ability to use a core set of personnel through all project phases, including development, test, and operations.
- The need to demonstrate a low cost approach to mission operations which can be used on future planetary missions
- The requirement to complete all mission operations activities during the primary and extended missions (through August '98) for a total of $14 M (RY)
- The desire to maximize the science and technology return of the mission without driving operations costs

The mission operations system that best suits these requirements uses a "skunkworks" concept in which operations are performed with minimal formality and compartmentalization. The associated team structure is relatively flat with minimal dependence on intermediate management and interface positions. The focus of this team is small group of people who are empowered to perform all key operations activities. These individuals, called Flight Engineers, are cross-trained to obtain a general understanding of the mission, payload, flight system and ground system. The Flight Engineers are responsible for day-to day operations and quick reaction anomaly response. In addition, they work directly with the scientists and technologists to plan the surface mission. The Flight Engineers are also responsible for coordinating all uplink and downlink activities, including hands on Use of the GDS toolset.

The Flight Engineers have genera] knowledge of the flight and ground systems, but are supported by subsystem specialists with dc.tailed knowledge. Subsystem engineers are responsible for maintaining and upgrading the GDS and spacecraft analysis tools. In addition, subsystem analysts are needed to perform off-line performance assessment and characterization. In some cases (particularly AACS and navigation), the subsystem engineers will be directly involved in the operations process due to their highly specialized knowledge. Subsystem engine.crs will also play a key role in analyzing anomalies and developing resolution and workaround plans.

The third component of the flight team is the group of scientists, experiment engineers, and technologists who perform the. mission investigations. These individuals form a single Experiment Team which includes the instrument teams, the participating scientists, and the rover operations team. The key responsibilities of this Team are to develop operations plans that satisfy the key experiment objectives, work with the Flight Engineers to develop and implement the necessary command sequences, monitor and maintain the health of the rover and instruments, and perform experiment data analysis. An assumption inherent in the Mars Pathfinder operations concept is that most members of the Experiment Team are in residence at JPL during key mission events.

The final members of the flight team are representatives from other JPL organizations dedicated to supporting Mars Pathfinder operations. This includes support personnel from the Multimission Image Processing Laboratory (performing science data processing), Deep Space Network operations (coordinating tracking support for the project), and the institutional Multimission Ground Data System Data Delivery Teams (providing the interface between the project GDS and the DSN data system).

Figure 3 shows the detailed team structure for Mars Pathfinder, including maximum workforce estimates. Detailed cost estimates show that this level of staffing satisfies the funding constraints with acceptable margins.

OPERATIONAL PROCESSES

The project has devc.loped top-level processes to define how this organization will operate. These processes differ depending on whether the spacecraft is in cruise or landed operations.

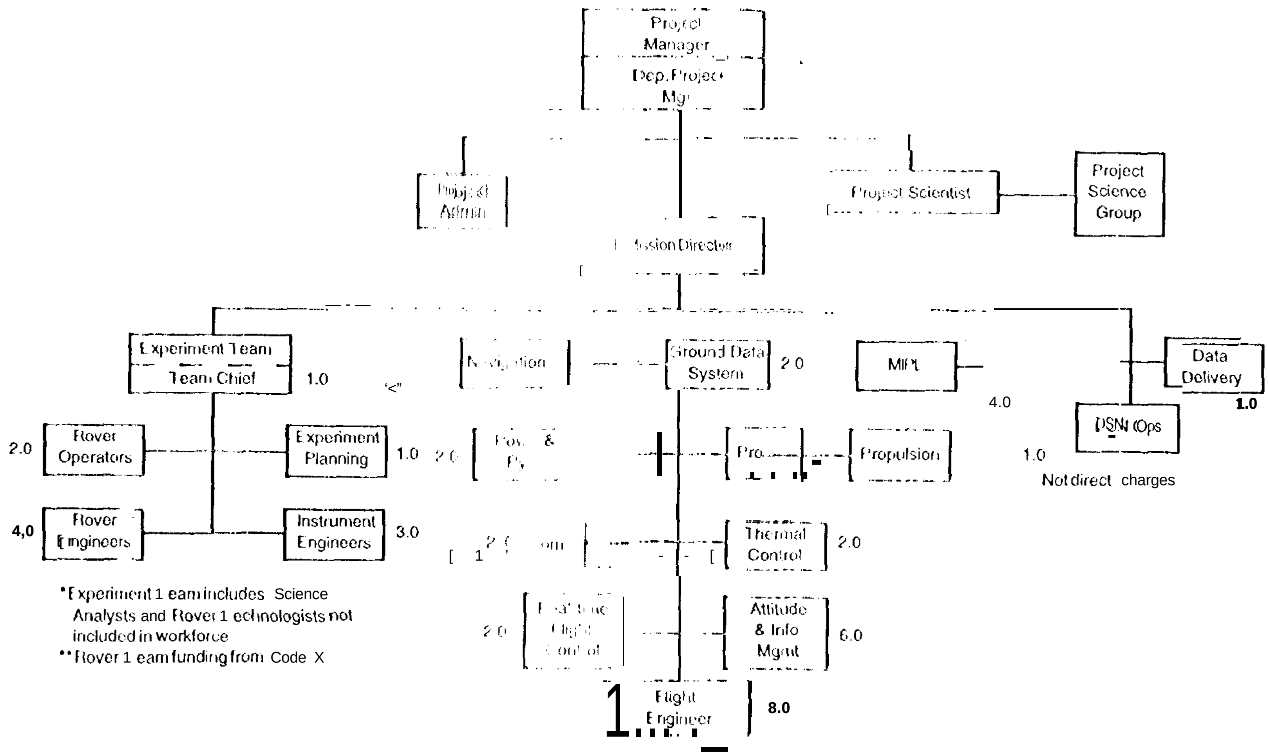

Figure 3. Mars Pathfinder Mission Operations Organization Structure (including workforce)

Cruise Operations Processes

Cruise operations are characterized by relatively long quiescent periods punctuated by a few key activities. Figure 4 shows a timeline of the key activities performed during cruise. Several background downlink analysis functions are performed throughout cruise, including real-time telemetry monitoring, spacecraft subsystem health monitoring and analysis, payload health monitoring, and analysis, and orbit determination. Uplink activities occur in support of the periodic special activities. The space.craft does not require a long term running sequence to operate, so the project has chosen to implement a mini-sequence driven process. Each key activity is performed using a simple mini-sequence. These mini-sequences can either be stored on the spacecraft (in the case where an activity is performed multiple times) or can be developed and uplinked when ground interaction is required (in the case of a trajectory correction maneuver where the maneuver depends on the most recent navigation data). This near real time process is possible because there are relatively few activities to perform and because sequencing high level commands is quite simple.

Surface Operations Processes

Surface operations are considerably more challenging than cruise because of the level of environmental uncertainty and the speed at which decisions must be made. As a result, the project has spent considerable effort defining detailed operational processes. A number of time critical activities are performed during the first day of surface operations (called Sol 1). Figure 5 shows a flowchart of the major spacecraft and ground activities required between landing and rover deploy. A number of key decision points are apparent, including whether to unlock the camera head, deploy the high gain antenna, unfurl the rover deploy ramps, and deploy the rover. Project personnel are developing detailed telemetry evaluation criteria needed to make each of these decisions. These criteria form a checklist which should allow timely and informed decisions. Most of the sequences needed to conduct these initial activities (except for the actual rover deploy sequence, which depends on the terrain

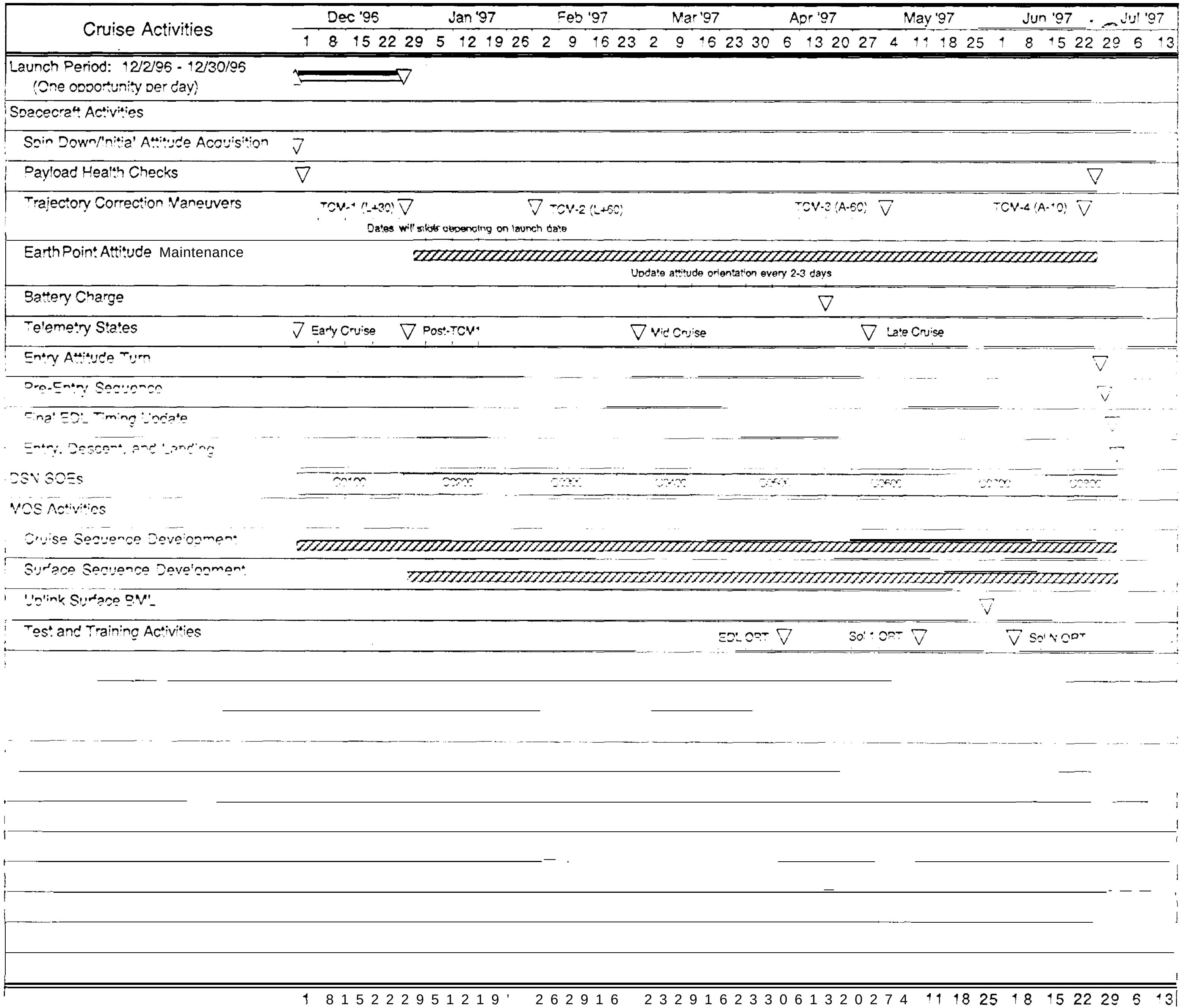

Figure 4 Cruise Operations Timeline

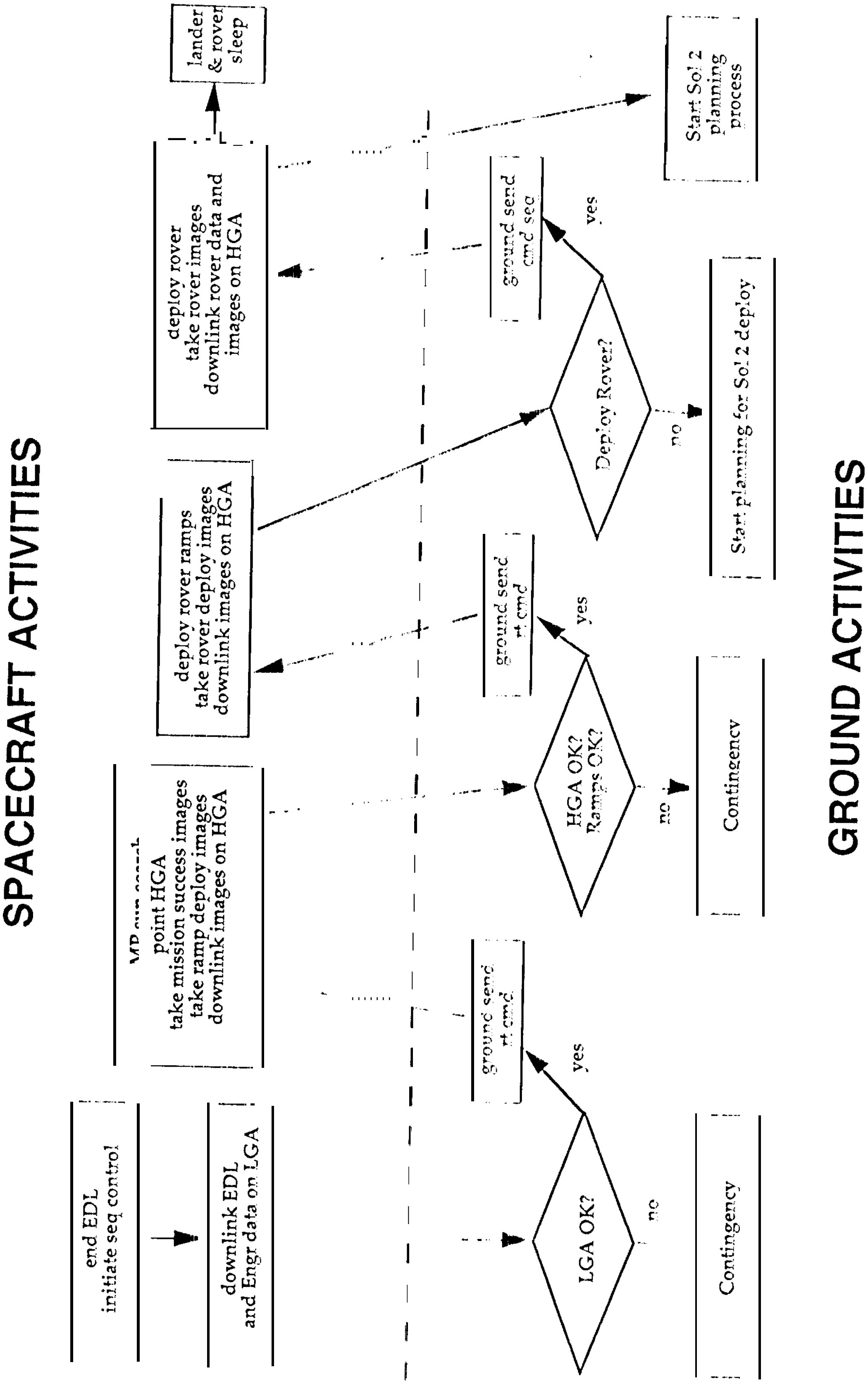

Figure 5. Sol 1 Decision Process

characteristics) will be loaded on the spacecraft before entry. These sequences have been designed to be resilient to delays in the decision process, and to provide fallback options in case of contingency. Command activities should be principally limited to activating these stored sequences.

The surface operations process after rover deploy changes significantly from Sol 1. One major difference is that there is only one command cycle each sol instead of several. The decision process behind each of these command cycles is more complex, moreover, because there are more choices available than on sol 1. The fundamental assumption behind the normal surface operations process is that small changes in the daily operations plan are likely each day. Changes are likely because our knowledge of the environment and lander response will improve with time and because the rover provides a level of flexibility to the scientists that is unprecedented. The high level objectives of the mission will not change, but the specific image sets, rover traverses, and Alpha-Proton-X-ray spectrometer data sets which are collected will certainly be modified.

Figure 6 shows a process timeline for normal surface operations. Daily operations of the lander and rover occur between about 6 a.m. and 3 p.m. (Local Solar Time at the lander). Thermal conditions prevent significant operations before 6 a.m., and the Earth sets below the horizon at about 3 p.m. The daily command session will generally be performed each morning (for about 1 hour), and most of each day's data will be telemetered during a three hour pass just before Earth set. Flight team activities start with the receipt of each day's telemetry data. The team has approximately 16 hours before commands for the next day's activities must be radiated to the spacecraft (the Mars day is about 40 minutes longer than the Earth day). The major activities performed during that period are to perform an assessment of the lander and rover's performance, review and possibly update the next day's mission plan, modify the rover and lander sequences, validate these sequences, and uplink them to the lander.

Accurate assessment of the spacecraft state is a prerequisite for each day's planning and sequencing activities. A system level perspective is needed, because the subsystems are highly integrated. This is particularly true of power and thermal control, which depend strongly on the operational scenario and the states of the other hardware components. An integrated engineering assessment task has been identified as a key element of the overall operations process. This task is performed immediately after telemetry is received to provide a quick-look assessment of the spacecraft. Detailed subsystem assessments of the telemetry are also performed in parallel over a longer time period. This quick-look assessment jump starts the subsequent uplink planning process and quick anomaly response.

The first activity in the daily uplink process is to replan and update the overall mission scenario. This activity is potentially the most time consuming because it requires detailed negotiations between science, rover, and lander engineering personnel. The project has attempted to streamline this activity by consolidating all experiment personnel into one team, empowering the flight engineers to work directly with the scientists (eliminating as much top-down management involvement as possible) and by using a sophisticated planning tool with detailed spacecraft behavioral models. This tool reduces the number of iterations needed to develop a new plan, and also provides a nearly complete command sequence. Combining the planning and sequence development step greatly reduces the time needed for sequence integration. Once sequences have been completed, the critical ones will be validated on a high fidelity hardware testbed.

OPERATIONS TEST AND TRAINING

Operational process validation is the principle objective of an exhaustive MOS test and training program planned for the period between July 1996 and December 1996, through exhaustive test and training activities. Planning is under way for a set of full-up operational rehearsals that will be conducted using the flight hardware testbed. These tests are a component of the project's risk mitigation plan, in that both nominal and contingency scenarios will be examined. Project personnel are currently developing the

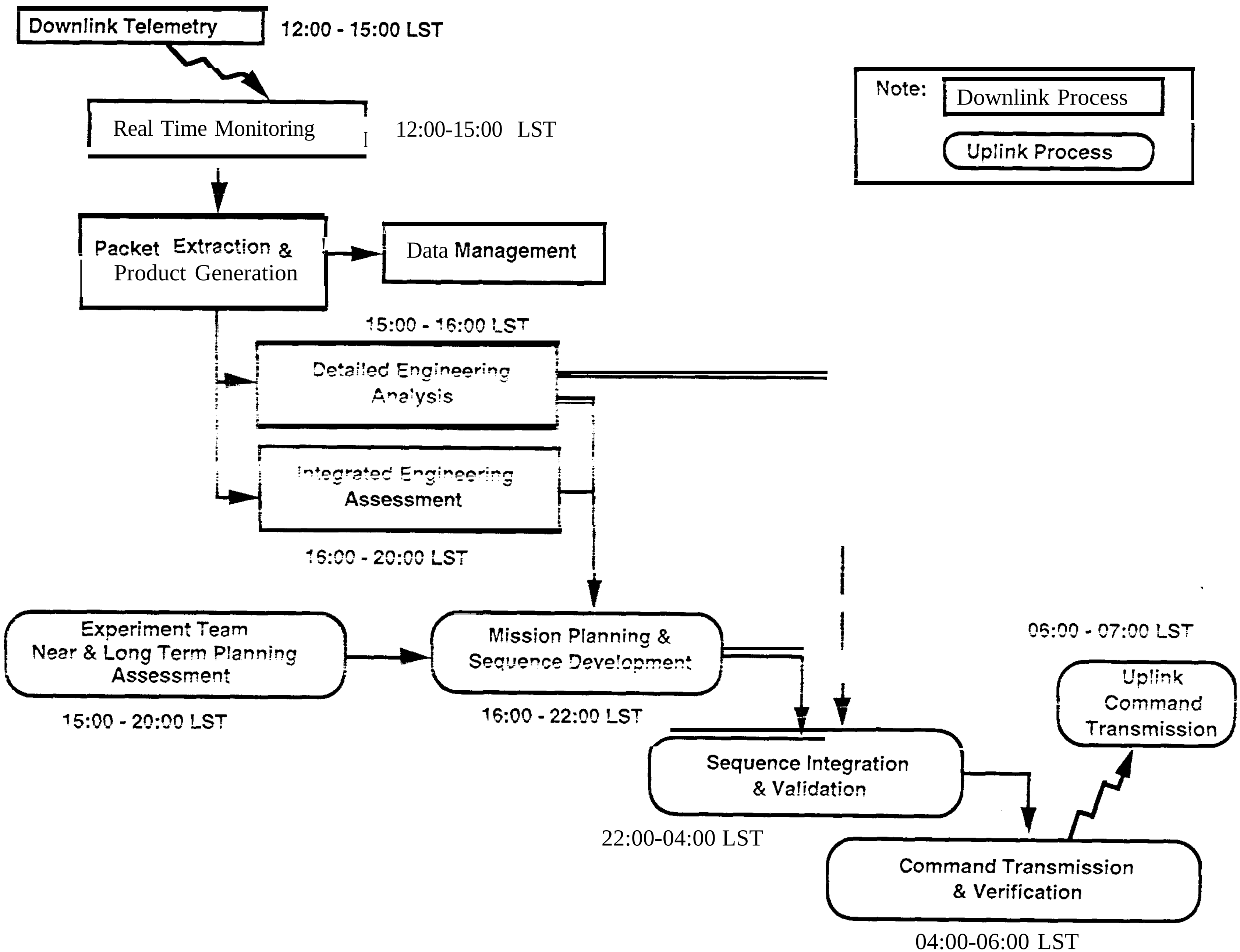

Figure 6. Surface Operations Process Timeline

detailed operational procedures that are needed for these tests.

Flight team training is also a key element of the Mars Pathfinder operations concept. Although all operations personnel participated in development and test, some cross-training will need to be performed to familiarize them with all aspects of operations. This is especially true of the Flight Engineers, who need to have broad knowledge of the entire flight and ground systems. A set of learner focused training sessions is currently being developed and will be completed by this summer. Some formal GDS toolset training is also required, but most members of the flight team are getting hands-on experience using the GDS during the spacecraft test program. On-going team training may be required during cruise, but the short mission duration should mean that the same core flight team will remain throughout the primary mission.

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